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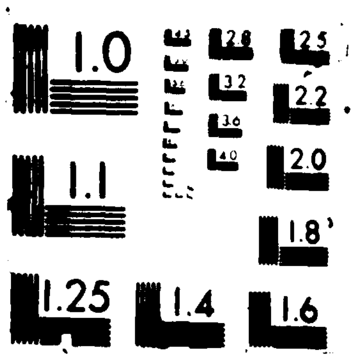
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THESIS

MEASUREMENTS OF GAS TURBINE COMBUSTOR AND ENGINE AUGMENTOR TUBE SOOTING CHARACTERISTICS

by

Thomas A. Grafton

September 1987

Thesis Advisor: D. W. NETZER

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A methodical investigation was conducted to examine soot particle sizing techniques and data acquisition apparatus so as to better understand soot particle properties in and immediately aft of a typical gas turbine combustor. Three wavelength light transmittance and multiple angle forward light scattering particle sizing techniques were used. The original objectives of this thesis were (1) to modify the existing hardware to better simulate the flow behavior in an actual engine, (2) to obtain accurate particle sizing using a combination of transmittance and scattering measurements within the T-63 combustor, (3) to explore the effects that augmentor tube flow rate has on particle agglomeration and mass concentration, and (4) to re-examine the effects that varied fuel-air ratios have on the exhaust particle mean diameter. Mean particle sizes were found to be between .77 microns and .80 microns at the exit of the augmentor tube.

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Measurements of Gas Turbine Combustor and Engine Augmentor Tube Sooting Characteristics

by

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B.S., Southern Illinois University, 1971

Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

A methodical investigation was conducted to examine soot particle sizing techniques and data acquisition apparatus so as to better understand soot particle properties in and immediately aft of a typical gas turbine combustor. A modified T-63 combustor with data acquisition stations set in the combustor, in the combustor exhaust can, and in a perpendicular plane across the aft end of an exhaust augmentor tube, served as the experimental apparatus. Three wavelength light transmittance and multiple angle forward light scattering particle sizing techniques were used. The original objectives of this thesis were (1) to modify the existing hardware to better simulate the flow behavior in an actual engine, (2) to obtain accurate particle sizing using a combination of transmittance and scattering measurements within the T-63 combustor, (3) to explore the effects that augmentor tube flow rate has on particle agglomeration and mass concentration, and (4) to re-examine the effects that varied fuel-air ratios have on the exhaust particle mean diameter. Objective (1) was achieved as well as a portion of objective (2). Due to instrumentation difficulties, objectives (3) and (4) were not attempted. Mean particle sizes were found to be between

.77 microns and .80 microns at the exit of the augmentor tube. Recommendations to improve future experiments are discussed.

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NOMENCLATURE

a	Constant in upper limit distribution function, 1.13
A	Cross-sectional area of particle
AR	Augmentor tube augmentation ratio, $\dot{m}$ pumped/$\dot{m}$ combustor
d, D	Particle diameter
D_m	Maximum particle diameter
D_{32}	Volume-to-surface mean diameter
F	Fuel-to-air ratio, Fraunhofer function
I	Intensity
J_1	Bessel function of order 1
L	Path length containing particles
m	Index of refraction of particles
$\dot{m}$	Mass flow rate
M	Mach number
N	Number concentration of particles
Q	Dimensionless extinction coefficient
$\bar{Q}$	Average dimensionless extinction coefficient for polydispersion
R	Gas constant
S	Exhaust nozzle - augmentor spacing
T	Temperature, transmittance
T_t	Stagnation temperature
V	Velocity
α	Particle size parameter, $\pi D_m/\lambda$

γ	Ratio of specific heats
δ	Constant in upper limit distribution function, 1.26
θ	Scattering angle
λ	Wavelength
ξ	D/D_m
ρ	Density of particle
σ	Standard deviation of particle size distribution

ACKNOWLEDGEMENTS

This thesis was a rewarding learning experience that would not have been possible without the help of several teachers. I learned technical expertise from Mr. Don Harvey and Mr. Harry Conner who either built or taught me how to build my experimental apparatus. Mr. Pat Hickey taught me technical drawing and technical planning and I learned propulsive and optical theory from Professor David Netzer. I sincerely thank each and every one of these teachers for the leadership, understanding, patience, and perserverence they showed in the monumental task of educating me. Finally, I would like to thank my wife Minna for her understanding and support during this thesis project.

I. INTRODUCTION AND BACKGROUND

All Navy and Air Force jet engines must undergo a scheduled phase maintenance process during which the engine must be statically tested. These uninstalled engine tests are performed in an engine test cell. The test cell, which consists of a thrust stand for the turbofan/turbojet, an augmentor tube to prevent exhaust recirculation and to cool the exhaust products and various noise suppression devices, is subject to strict regulations and guidelines set forth by the Environmental Protection Agency that address exhaust emissions of air pollutants. In addition to the federal regulations, many states have legislated even more stringent requirements to further curb pollutant emissions.

Because of fiscal constraints and other reasons, few new test cell facilities are being built to meet these increasingly restrictive regulations. Many short term solutions are being studied and one of these measures is the use of various fuel additives to curtail or eliminate exhaust pollutants produced by turbojet/turbofans while operating in test cell facilities.

Soot production not only causes atmospheric pollution and reduced visibility, but also shortens the life cycle of the engine hot section, adversely affecting

engine reliability. Tactically, most fighter pilots live by the old adage, "Keep sight, win the fight," and it is common knowledge that the F-4 Phantom's smoke trail allowed unaided visual acquisition by adversary pilots in excess of 20 nautical miles. A fuel additive that would reduce or eliminate an aircraft's smoke trail while not affecting performance would be invaluable to the Navy and Air Force fighter communities.

Since 1982, several Naval Postgraduate School thesis efforts have been directed at determining the effects of fuel composition and additives on exhaust soot concentrations and size. To do this, a full scale gas turbine test facility, incorporating the combustor section from an Allison T-63-A-5A engine, was developed. Some of the significant results from the last five years of research are:

1. Additives can increase or decrease soot size without effecting mass concentration.
2. Additives were less effective with lower combustor air inlet temperature.
3. Exhaust D_{32} was independent of fuel composition and fuel-air ratio.
4. A soot mean index of refraction of 1.95 - 0.66i resulted in the best data correlation for light transmission measurements.

In earlier investigations it was observed that additives sometimes had a different effect in the combustor test apparatus than in the actual engine. This was thought to result from the lack of work extraction when a turbine is not employed. Previous results also were obtained using only limited measurements of forward light scattering.

The original objectives of this thesis were to:

1. To modify the existing hardware to better simulate the flow behavior in an actual engine,
2. To obtain accurate particle sizing using a combination of transmittance and scattering measurements within the T-63 combustor,
3. To explore the effects that augmentor tube flow rate have on particle agglomeration and mass concentration, and
4. To re-examine the effects that varied fuel-air ratios have on the exhaust particle mean diameter.

II. DESCRIPTION OF EXPERIMENTAL APPARATUS

The experiment basically used the same apparatus utilized by Young [Ref. 1], but with several equipment additions and modifications. There were two purposes for equipment modifications. The first purpose was to make the Allison T-63-A-5A engine, without a power turbine or compressor, perform more closely with an unmodified "in-use" turboshaft engine; and secondly, to modify the optics in order to obtain more accurate particle sizing data. The following paragraphs describe the apparatus and modifications.

A. COMBUSTOR

A full-scale Allison T-63 combustor was used in the experiment. However, prior to data collection runs, the entire engine was dismantled and cleaned, and all gaskets between the combustor and turbine nozzle block were replaced with new factory parts. Included in the combustor section was the ignitor plug, combustor housing, and the turbine nozzle block. A new heat resistant #316 stainless steel exhaust housing, which was 15% longer than the exhaust housing used previously, was built to accommodate a quench manifold. An additional 0.5 lbm/sec of air at approximately 40°F was supplied to the combustion section just aft of the turbine nozzle block. The purpose of the quench manifold was to better

simulate an actual T-63 engine where exhaust gases from the combustor are quenched by turbine work extraction. Figure 1 is a schematic of the combustor.

B. AIR SUPPLY

A 3000 psi tank storage system provided the compressed air necessary for the T-63 combustor. Air flowed from the tanks through flow regulators and then entered the combustion chamber through two tubular ducts on either side of the engine case. A separate set of piping supplied the necessary mass flow to the air quench manifold. A remote controlled air flow system was operated from the system control panel inside the control room. A pressure regulator provided the pressure for a dome loaded pressure regulator. The latter provided the set pressure to the sonic choke which was used to measure the mass flow rate of air to the combustor. The temperature and pressure transducers at the sonic chokes supplied the remaining measurements necessary for the computer to calculate the mass flow rates for the experimental run.

C. FUEL SUPPLY/AIR HEATER/ADDITIVE PUMPS

The fuel supply, vitiated air heater, and additive pump systems are discussed in detail by Young [Ref. 1]. No changes to these systems were made for this experiment.

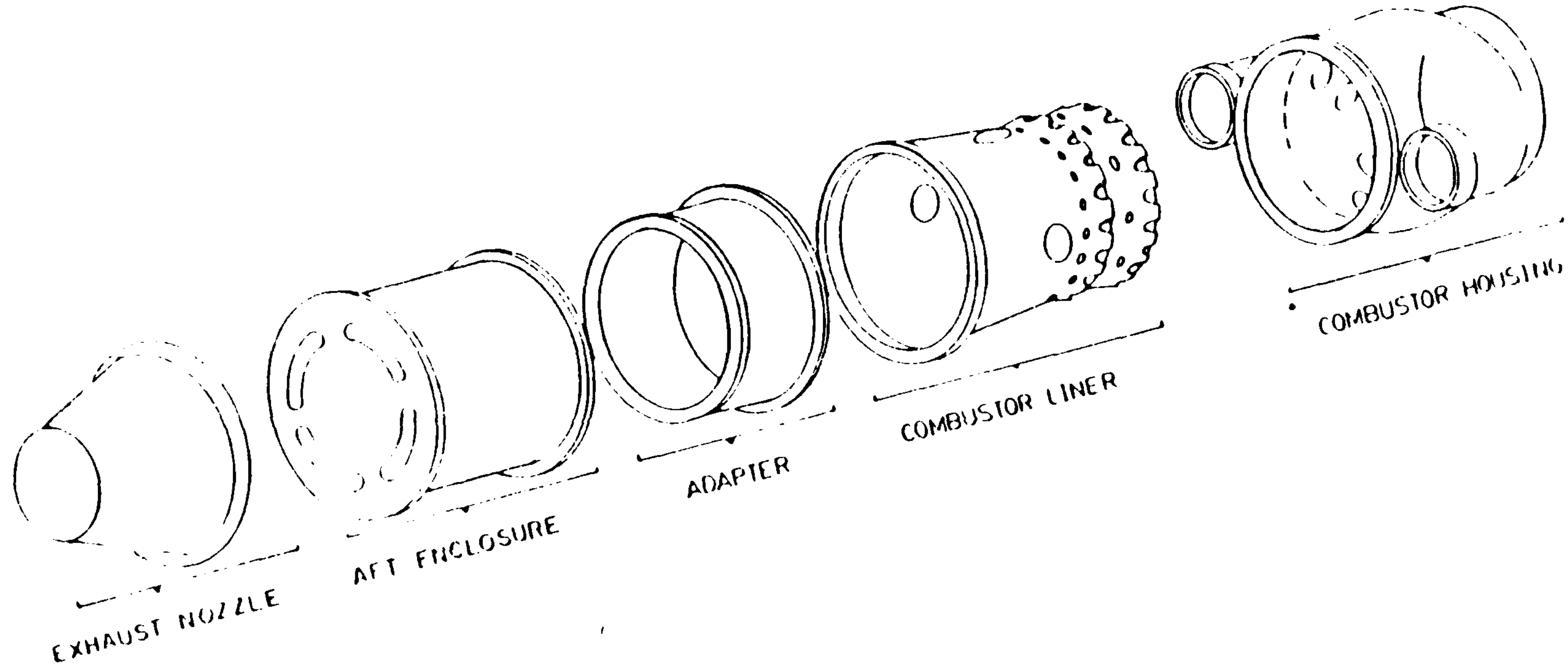


FIGURE 1. T-63 COMBUSTOR SCHEMATIC [Ref. 1]

D. THERMOCOUPLES

Seven thermocouples were used in the experiment to monitor the temperature profile around the combustor and the exhaust can. Five of the thermocouples were located in the combustor section. The remaining two were added to measure the exhaust temperatures before and after the quench manifold. Additionally, the thermocouple located prior to the quench manifold sent analog temperature readings to strip charts in the control room, where the exhaust gas temperature was constantly monitored for a possible engine overtemp. An overtemp condition was considered to occur any time the exhaust gases reached 1350°F or higher. The engine was immediately shut down when an engine overtemp occurred.

The thermocouples were connected by direct wires to the Hewlett-Packard data acquisition system located in the control room area. Locations of these thermo-ouples are depicted on Figures 2 and 3.

E. AUGMENTOR TUBE

Four inch, six inch, and eight inch augmentor tubes were available for use in the experiment. Their length was six feet. The exhaust augmentation ratio is the ratio of augmentor tube suction flow rate to exhaust nozzle mass flow rate. The various sizes of augmentor tube diameters create different amounts of cold air induction. They may also result in different soot

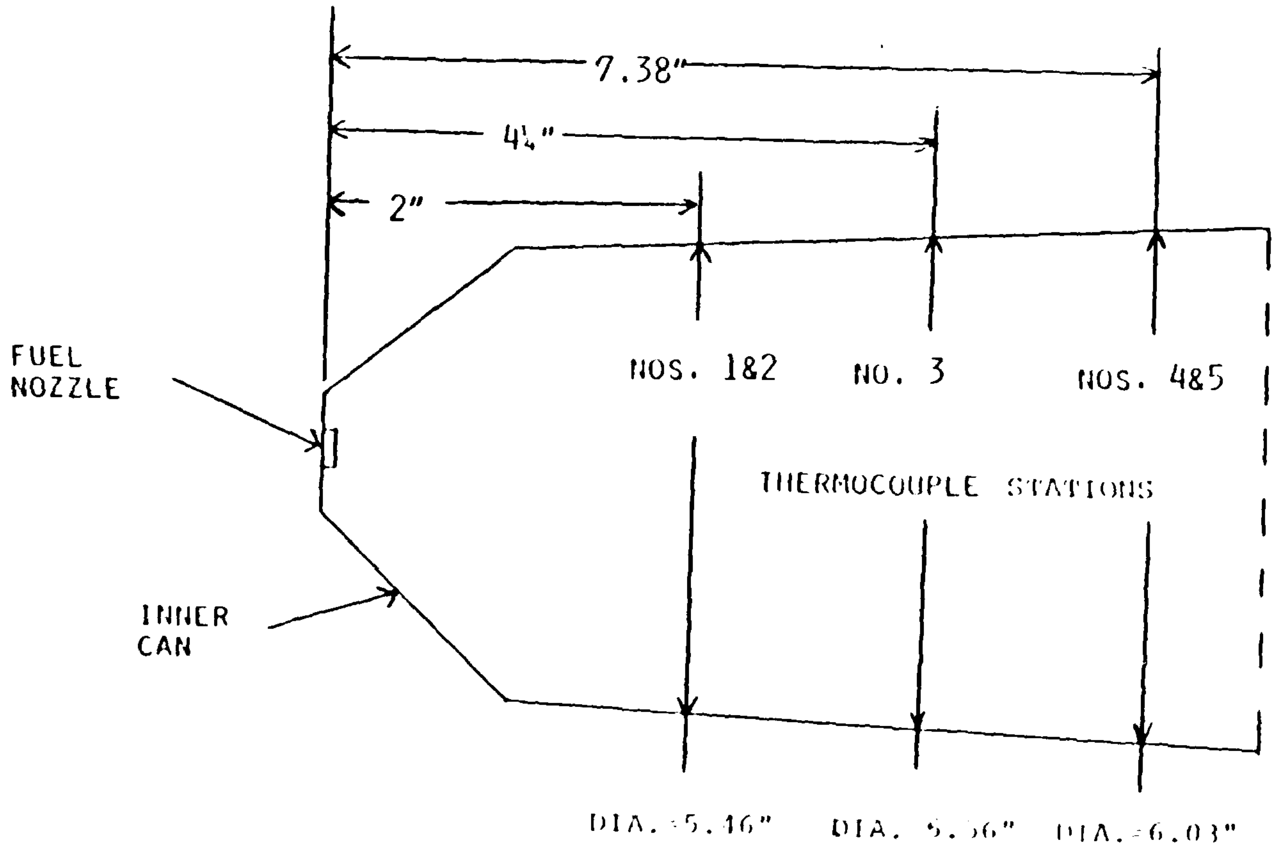
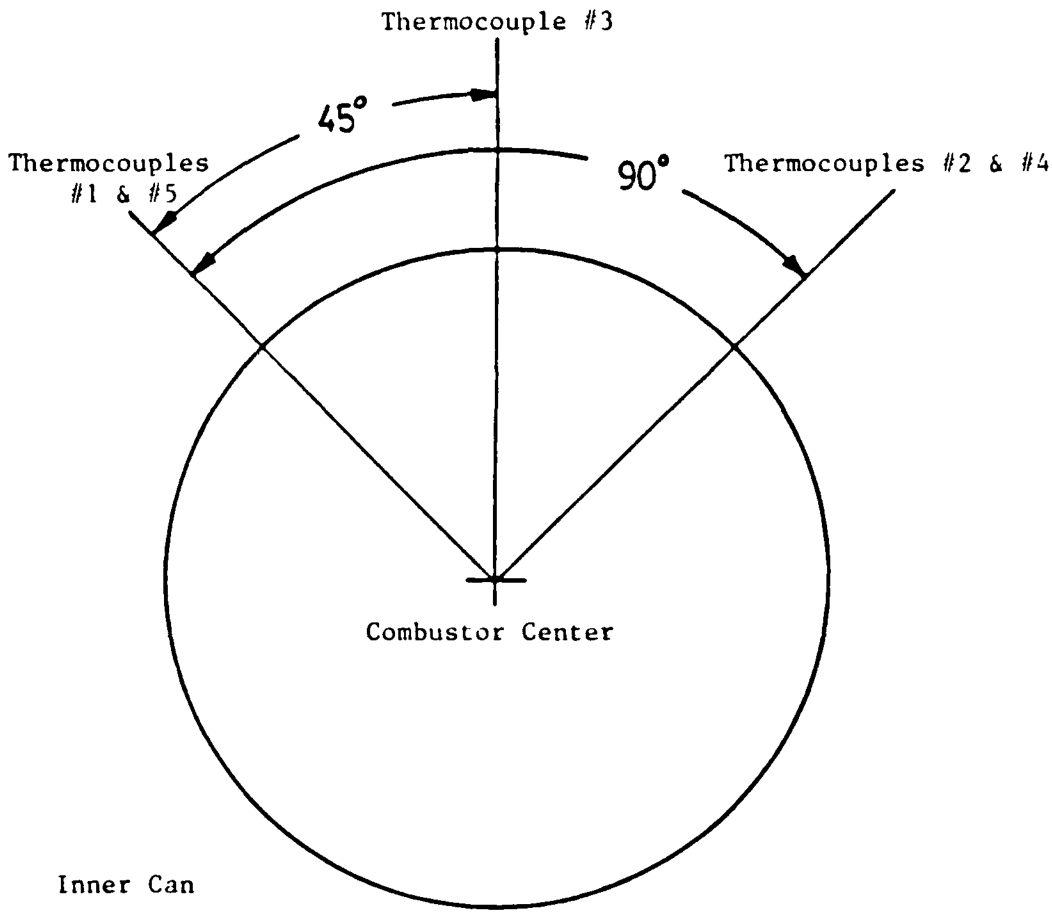


FIGURE 2. SIDE VIEW OF T-63 THERMOCOUPLE LOCATIONS [Ref. 2]



Distance of Thermocouples From Combustor Center

#1	2.23"
#2	1.73"
#3	2.28"
#4	2.01"
#5	Not Used

FIGURE 3. COMBUSTOR THERMOCOUPLE PLACEMENT (END VIEW) [Ref. 2]

sizes at the exit and different augmentor exhaust temperatures. A physical description of the augmentor tube is depicted in Figure 4. A physical description of augmentation ratio is depicted in Figure 5.

F. LIGHT TRANSMITTANCE APPARATUS

There were two primary methods used to size soot in this gas turbine combustor experiment. They were soot sizing by three wavelength transmittance measurements and soot sizing by forward scattering measurements. The theoretical basis for these techniques is discussed in the theory section of the thesis. It is important to look at the components of each system in detail. Figures 4 and 6 depict the entire T-63 and its particle sizing apparatus. First, consider the transmittance system.

A white light source with a light wavelength spectrum of 400 nm to approximately 1020 nm was placed so that a collimated light beam passed through the after portion of the motor, Figure 7. Initially, the beam was received by a fiber optics cable which carried the captured light to a trifurcated cable juncture. Here it was split into three paths and carried to three separate photodiodes. The light was processed by a narrow pass filter located on the top of each diode so that only a specific wavelength of light was permitted to pass through to the diode face. The wavelengths were

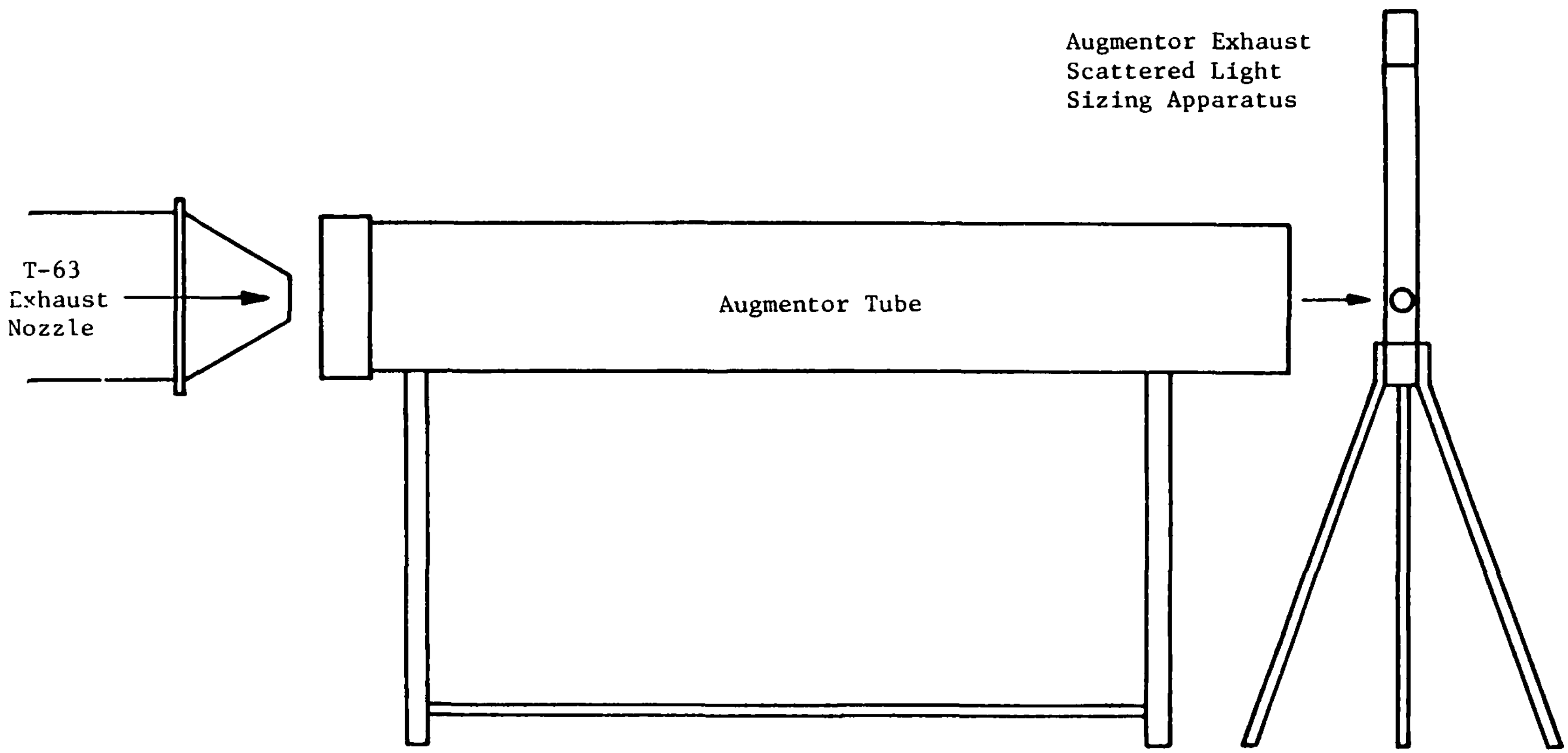


FIGURE 4. SIDE VIEW OF T-63 AUGMENTOR TUBE APPARATUS

$$\text{Augmentation Ratio} = \frac{\text{Secondary Mass Flow Rate}}{\text{Primary Jet Exhaust Mass Flow Rate}}$$

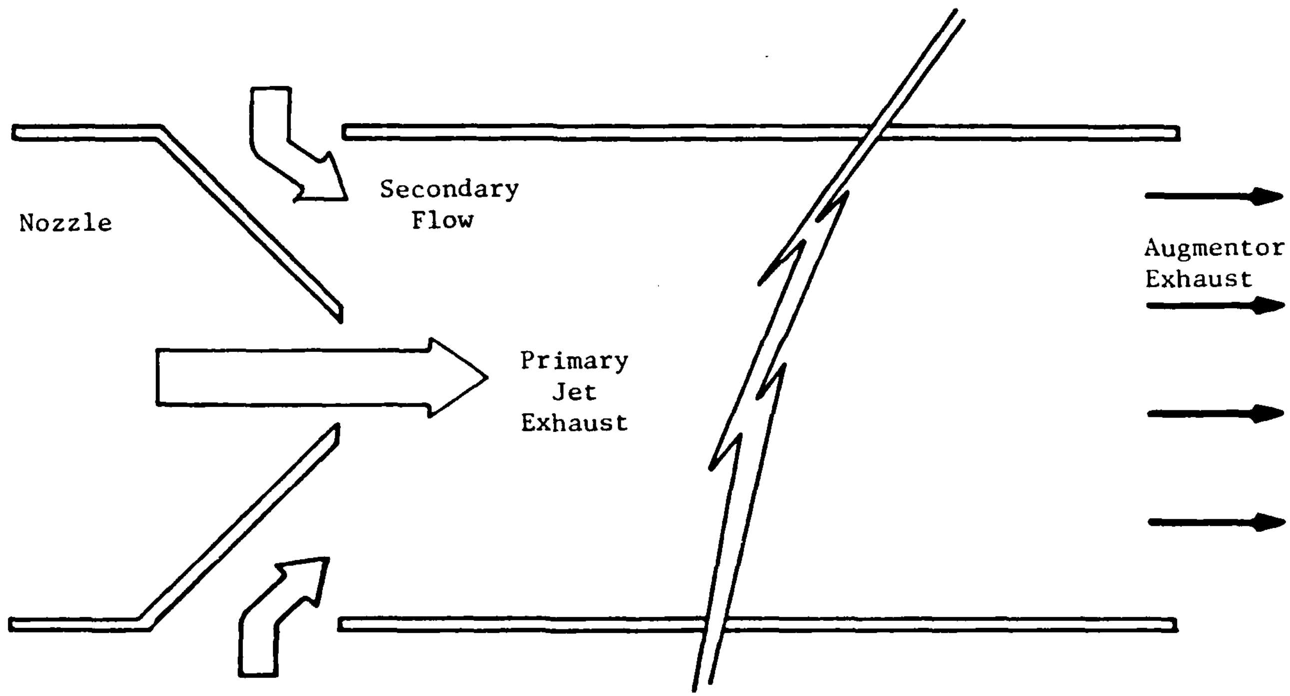


FIGURE 5. AUGMENTOR TUBE FLOW ENVIRONMENT [Ref. 7]

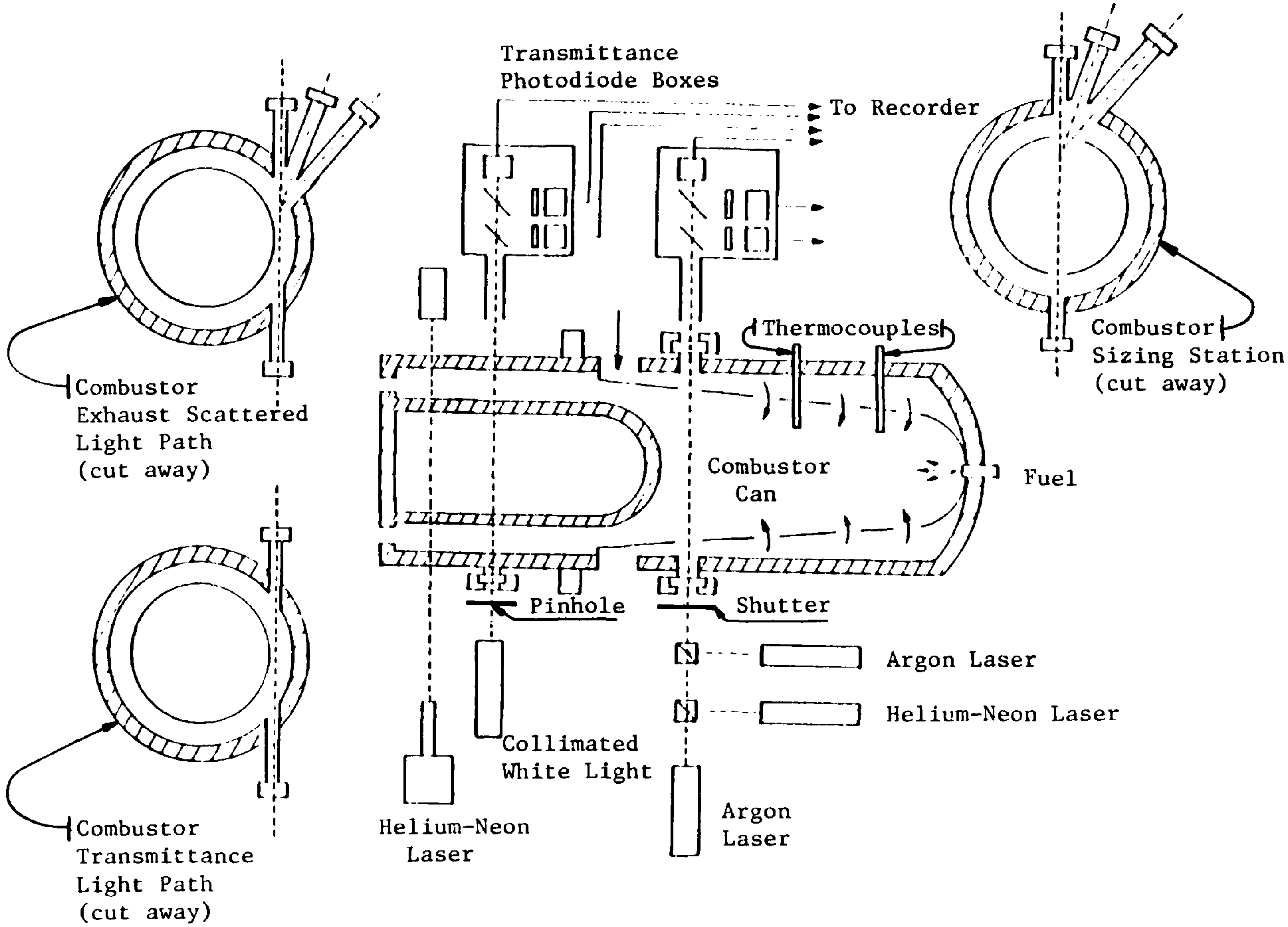


FIGURE 6. SCHEMATIC OF T-63 TEST APPARATUS (Adapted from Ref. 7)

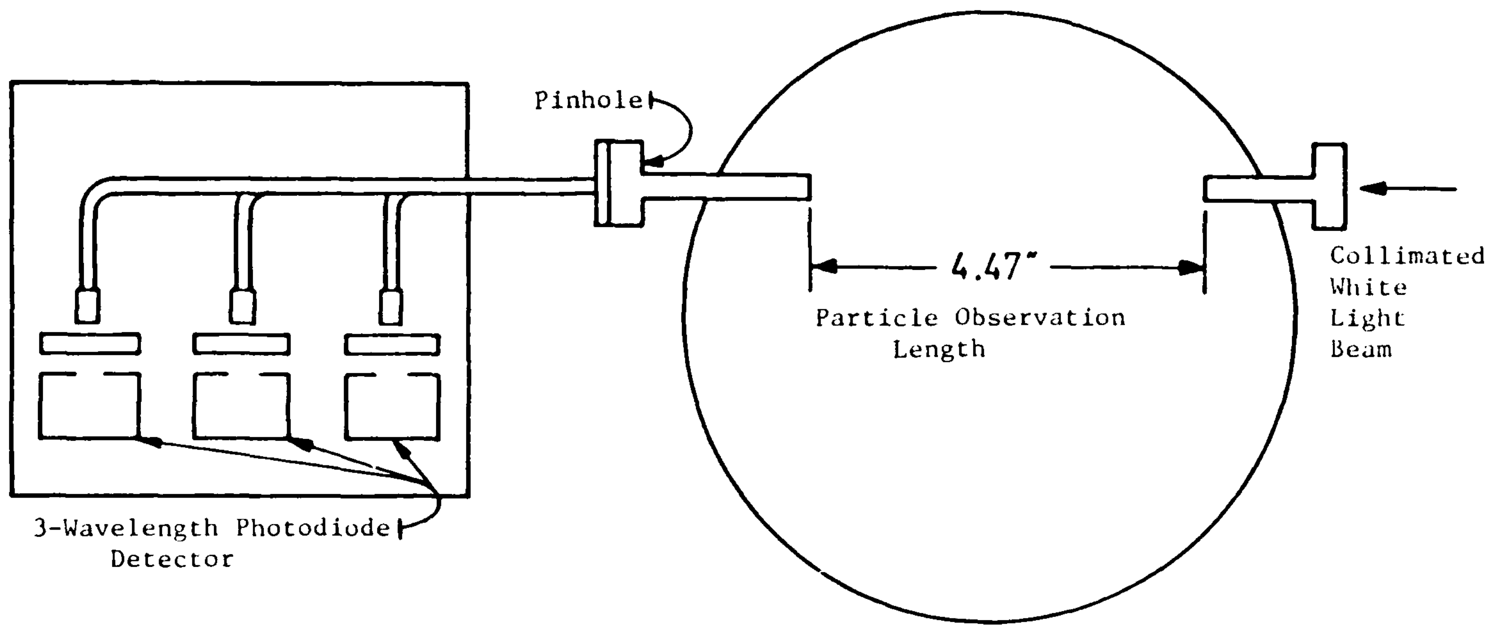


FIGURE 7. SCHEMATIC OF OPTICAL TRANSMITTANCE LIGHT PATH IN EXHAUST SECTION (END VIEW) (Adapted from Ref. 7)

initially chosen to be 450 nm, 650 nm, and 1014 nm, because these wavelengths were furthest apart in the available source light wavelength spectrum. Suffice it to say for now that the further apart the wavelength choices are, the better their ratioing capability and the more accurate the data can be. The voltage signals from these photodiodes were sent directly to the computer for data reduction.

In the combustion section, however, a white light source was not practical to use because the light emissions from the combustion process were of high intensity and too close to the wavelength spectrum of any white light source available for the experiment. Thus, three lasers were used, Figures 8 and 9. It was not possible with the available lasers to obtain as wide a spread in wavelength as desired. A trifurcated fiber optics cable was initially used to direct the laser light to three narrow pass filters of 488.0 nm (blue), 514.5 nm (green), and 632.8 nm (red) wavelengths. Two tunable argon lasers (514.5 nm and 488.0 nm) supplied green and blue light sources and a helium-neon laser supplied the red light source.

In previous tests it was found that the laser light was overwhelmed by the large amounts of white light generated in the combustor during the runs. A 90 Hz light chopper was therefore added at the input side

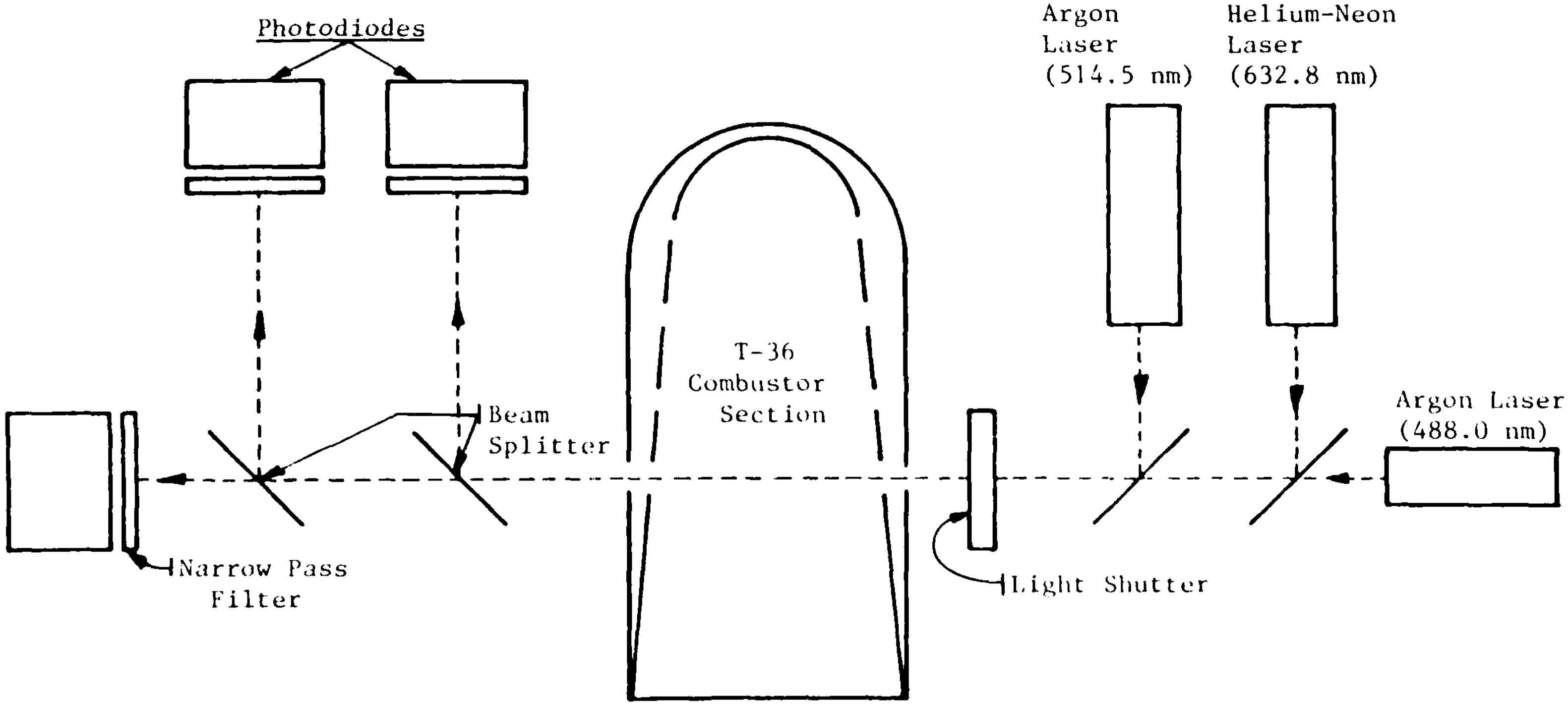


FIGURE 8. SCHEMATIC OF OPTICAL TRANSMITTANCE LIGHT PATH IN COMBUSTOR SECTION (TOP VIEW) (Adapted from Ref. 7)

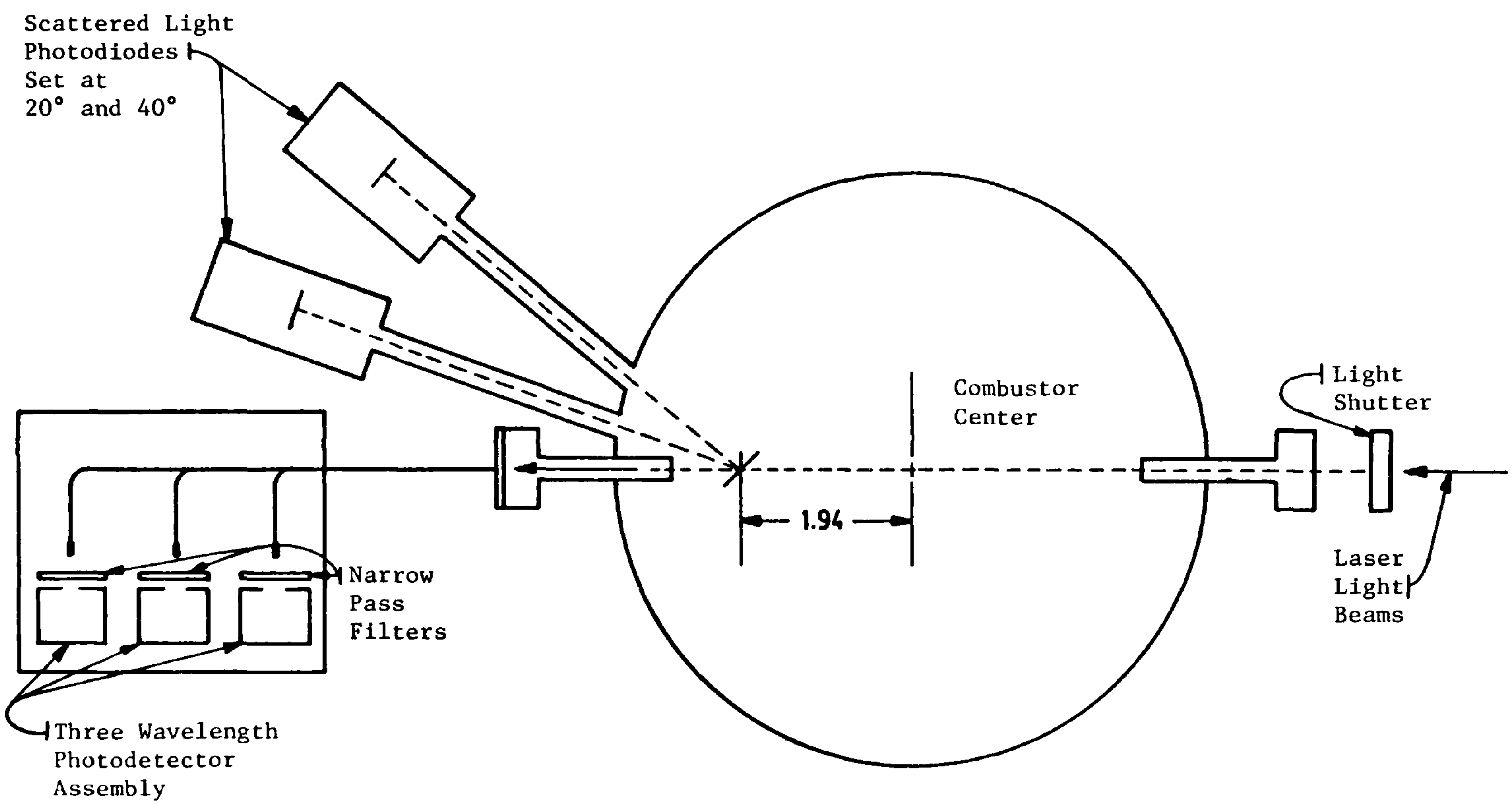


FIGURE 9. SCHEMATIC OF OPTICAL PATH IN MAIN COMBUSTOR SECTION (END VIEW) [Ref. 1]

of the combustor. The photodiode detectors sensed light from the combustion process as well as from the laser source light. A phase-lock amplifier was used to eliminate all light not at 90 Hz. Initial tests showed that the signal to noise ratio was such that laser light generally could not be separated from the combustor light. The chopper and phase-lock amplifier were therefore removed in later tests.

G. FORWARD LIGHT SCATTERING APPARATUS

The measurement of forward scattered light was the second method used for soot sizing in the experiment. The scattering measurement apparatus was placed at three stations on the T-63 gas turbine combustor and augmentor tube. The stations, depicted in Figure 6, were located in the combustor, in the exhaust can, and in the exit plane, immediately aft of the augmentor tube (Figure 10).

The combustor section apparatus consisted of 90 Hz chopped or unchopped 488.0 nm wavelength light, provided by an argon laser and two photodiode boxes positioned at 20° and 40°, each containing a photodiode and a narrow pass, laser line filter. The 488.0 nm wavelength light was chosen for the scattering measurements because it was the most powerful of the lasers available for experimental use and the majority of combustion process light was suspected to be in the

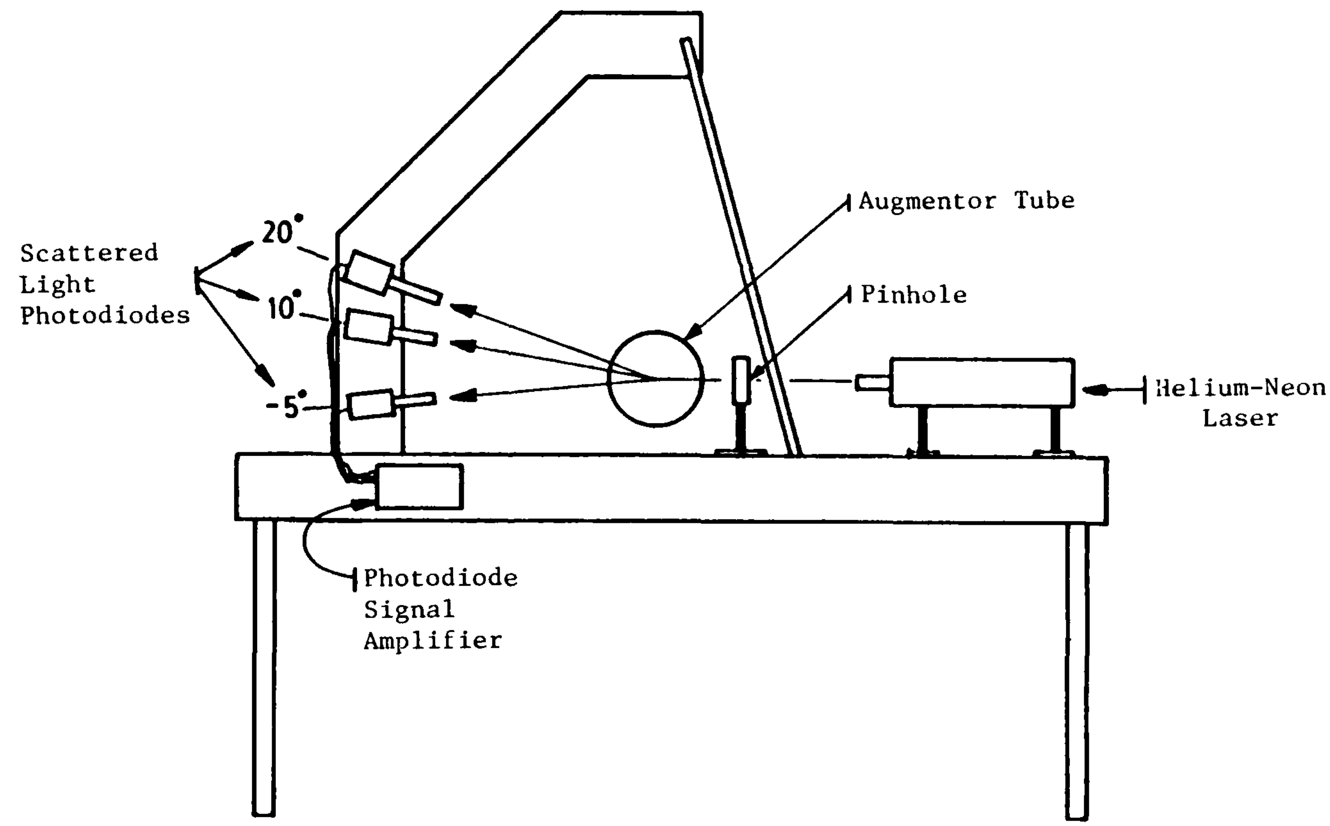


FIGURE 10. SCHEMATIC OF AUGMENTOR TUBE PARTICLE SIZING APPARATUS (END VIEW)

higher wavelengths. The helium-neon (632.8 nm) laser had the least power of the three lasers available for use. The tunable argon lasers operated at much higher output powers.

The exhaust section forward-scattering apparatus was the same as the combustor scattering apparatus except in two important areas. First, the laser light beam did not need to be chopped it, and, secondly, the laser light source was supplied by a less powerfu' helium-neon laser (Figure 11).

The aft-most light scattering apparatus was located at the exit plane of the augmentor tube, Figure 10. The set-up was exactly that of the exhaust equipment, except three diode boxes were used instead of two. Initially, they were set at angles of -5°. 10°, and 20° from horizontal. Further, a detailed description of the augmentor tube scattering apparatus is described by Young [Ref. 1]. Again, with the absence of combustion light in the exhaust and augmentor tube areas, signal voltages from the diodes were sent directly to the computer for processing and data reduction.

H. CONTROL PANEL AND DATA CAPTURING EQUIPMENT

A control room adjacent to the test cell provided a disturbance-free location to collect and reduce data as well as a safe place to control and observe the experiment. An observation window provided viewing of

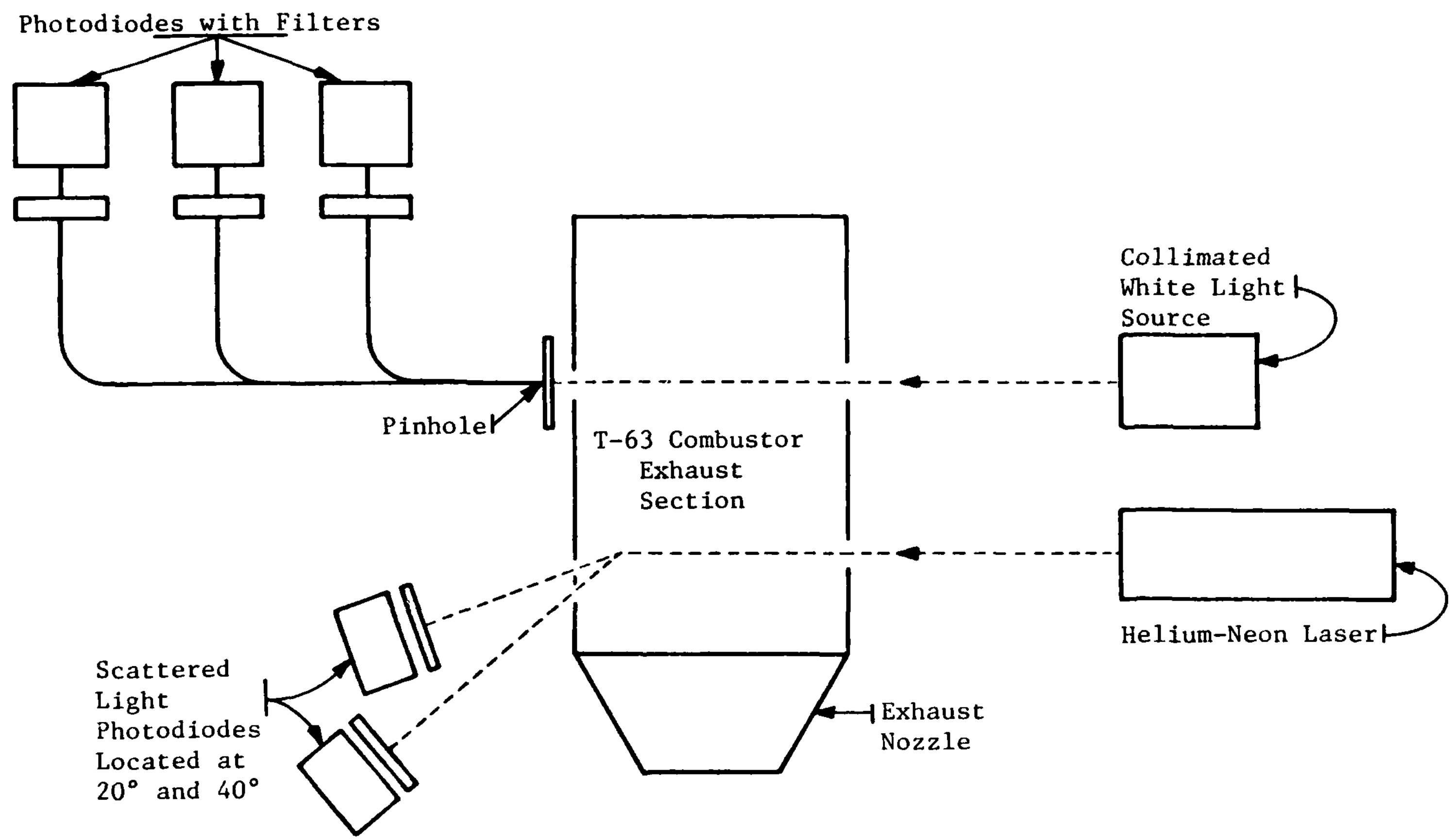


FIGURE 11. SCHEMATIC OF COMBUSTOR EXHAUST PARTICLE SIZING APPARATUS (TOP VIEW)

experimental operations under which a master control panel provided control signals to all vital elements. Fuel flow was controlled by a throttling valve. It was measured by a turbine flow meter which sent continuous data to a digital quage on the control panel and to the computer. Main air into the combustor and quench manifold was controlled by a single solenoid operated on-off switch. Fuel additives could be added to the various jet fuels tested by a swirl-type mixer, which blended the fuel and additive before it was passed to the combustor. Two precision metering pumps controlled the flow rate of additive. The pumping rates were controlled at the control panel.

III. THEORY

The entire experimental apparatus set-up was designed to measure soot size at various positions within the T-63 and aft of the T-63 using two measuring techniques; three wavelength light transmission measurements and forward light scattering measurements. These methods of measurement were chosen because they are non-intrusive to the flow within the motor and provided a continuous data measurement capability.

A. THREE-WAVELENGTH LIGHT TRANSMITTANCE TECHNIQUE

The general three-wavelength method has been presented by Cashdollar [Ref. 4] and his technique is briefly outlined below.

K. L. Cashdollar found that the size of soot particles and the mass concentration of the smoke could be measured by three-wavelength light transmission measurements. Specifically, by using the light transmission law for a polydisperse system of soot particles given by

$$T_\lambda = \exp\{-(3\overline{Q}C_m L/2\rho\ D_{32})\} \qquad (1)$$

where:

T_λ = Transmission at wavelength λ .

$\overline{Q}$ = Dimensionless average extinction coefficient for a polydisperse particle system.

C_m = Mass concentration.

L = Path length containing particles.

ρ = Density of particles.

D_{32} = Mean particle diameter based on the volume-to-surface area ratio.

Previous research [Ref. 5] discovered that if a log-normal particle distribution is assumed for smoke particles it could be shown that the average extinction coefficient depends primarily on the mean diameter (D_{32}) and the wavelength of light. Writing equation (1) for two wavelengths

$$T_{\lambda 1} = \exp\{-(3\overline{Q}_1 C_m L/2\rho\, D_{32})\} \tag{1a}$$

and

$$T_{\lambda_2} = \exp\{-(3\overline{Q}_2 C_m L/2\rho\, D_{32})\} \tag{1b}$$

The ratio of the logarithms of the two transmittances at any two wavelengths is equal to the ratio of the calculated dimensionless extinction coefficients for polydispersed particles, or:

$$\mathrm{Ln}\, T_{\lambda_1}/\mathrm{Ln}\, T_{\lambda_2} = \overline{Q}_1/\overline{Q}_2 \,. \tag{2}$$

A Mie-scattering computer program was obtained from the Pittsburg Mining Center, Bureau of Mines, which was written by Cashdollar [Ref. 4]. It yields graphs of extinction coefficient ($\overline{Q}$) versus volume-to-surface mean particle diamenter (D_{32}) and the ratio of extinction coefficient $\overline{Q}_1/\overline{Q}_2$ versus D_{32} (Figures 12 and 13). The

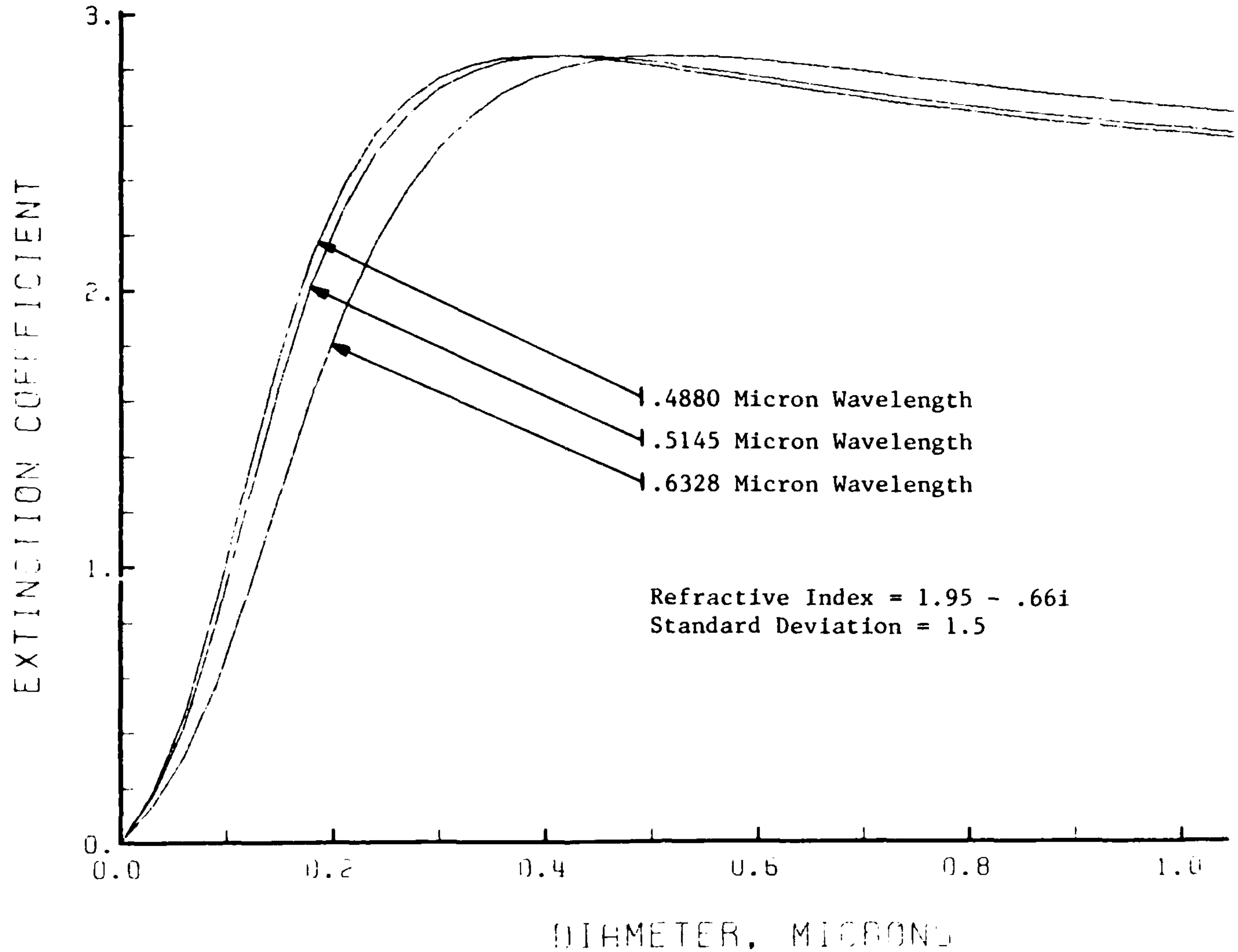


FIGURE 12. EXTINCTION COEFFICIENT VS. PARTICLE SIZE (D_{32})

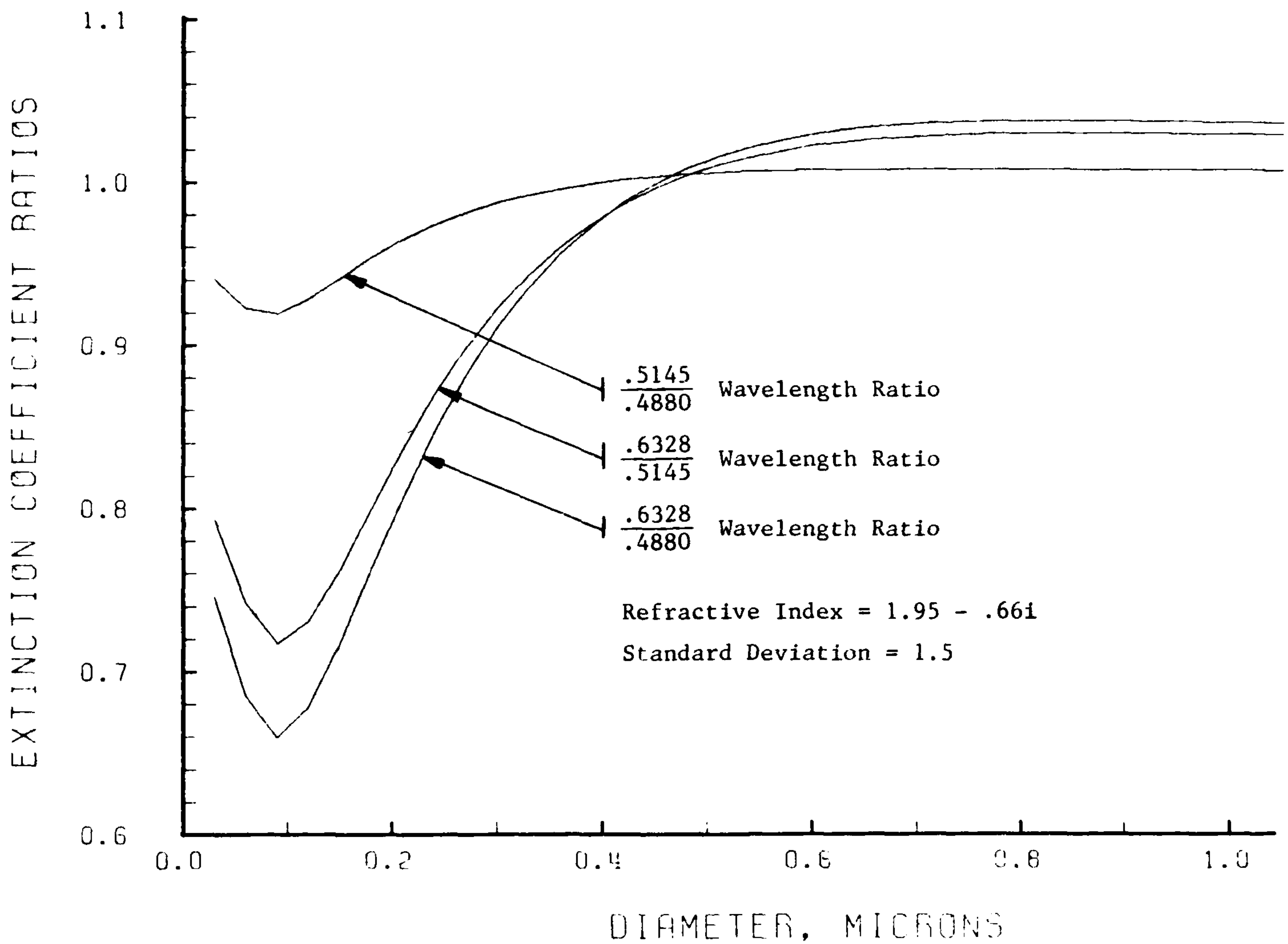


FIGURE 13. EXTINCTION COEFFICIENT RATIO VS. PARTICLE SIZE (D_{32})

program produced this information for various chosen complex indexes of refraction (m) and standard deviation of the particle size distribution. The standard deviations were chosen to be either $\sigma = 1.5$ or $\sigma = 2.0$, which assumes a monomodal particle distribution. Various values of index of refraction have been reported in the literature for carbon or soot, however, the primary value considered in this investigation was 1.95 - 66i.

Actual reduction of data was accomplished by the following method:

<u>Step 1.</u> The three transmittances T_λ's obtained experimentally were presented in the computer printout after each run.

<u>Step 2.</u> The transmittances were then adjusted to account for diode offset voltages and then log ratioed.

<u>Step 3.</u> With $\ln T_{\lambda_1}/\ln T_{\lambda_2}$, $\ln T_{\lambda_1}/\ln T_{\lambda_3}$ and $\ln T_{\lambda_2}/\ln T_{\lambda_3}$ calculated, the corresponding extinction coefficient ratios were known Equation (2).

<u>Step 4.</u> The theoretical extinction coefficient ratio plots for a particular m and σ were entered to find three values of D_{32}. If all three values were not nearly identical, either m and/or σ was incorrect. Subsequent graphs for different m and/or σ

were entered until the best correlation was obtained. This resulted in D_{32}, m and σ .

Step 5. With a consistent D_{32} known from Step 4, the plot o f $\overline{Q}$ vs D_{32} was used to find the extinction coefficient $\overline{Q}$.

Step 6. With $\overline{Q}$, T_λ , L and ρ , all known, the mass concentration of the soot could be found from:

$$C_m = -[2\rho D_{32} LnT_\lambda / 3\overline{Q}L] \quad . \qquad (3)$$

In summary, the three three-wavelength measurement method has five advantages: (1) it is a non-intrusive measurement method for particle size measurement, (2) it provides a continuous, timely source of measurement during actual run conditions, (3) it requires inexpensive apparatus, (4) data reduction is simple, and, finally (5) it can be used to very low transmittance values and still yield accurate mean particle size and particle concentrations. The disadvantages are: (1) that this method yields only mean particle size with assumed monomodal distribution, (2) it is limited to particles with diameters between approximately .05 and .5 microns, (3) a knowledge of the medium's index of refraction is required, and (4) the particle index of refraction is assumed independent of wavelength.

B. FORWARD LIGHT SCATTERING TECHNIQUE

The second method for soot sizing used in the experiment was a forward light scattering technique. Powell, et al. [Ref. 6] and Dobbins, et al. [Ref. 5] utilized Fraunhofer forward lobe diffracted light theory (diffracted light essentially consists of flared light beams that are formed from an incident light wave that encounters an obstacle or obstruction and is bent as the light passes near the obstacle) to determine the mean particle diameter of small polydispersed prticles. The The incident light was supplied by collimated laser light. These reference articles pointed out that the intensity of light at two angles $I(\theta_1)$, $I(\theta_2)$ can be ratioed and equated to the ratio of the Fraunhofer functions at those same angles or

$$\frac{I(\theta_1)}{I(\theta_2)} = \frac{F(\theta_1)}{F(\theta_2)} \tag{4}$$

where the Fraunhofer function is specifically defined for an assumed upper limit distribution function [Ref. 6] as:

$$F(\theta) = \int_0^1 (1+\cos^2\theta)[J_1(\alpha\theta\xi)/\theta\xi]^2 x \exp[-(\delta \ln(a\xi/1-\xi))] \frac{d\xi}{1-\xi} \tag{5}$$

where $\xi = D/D_m$

D_m = the maximum particle diameter

$$\alpha = \pi D/\lambda \tag{6}$$

$$D_m/D_{32} = 1 + a \exp(1/4\delta^2) \tag{7}$$

and a and δ are adjustable parameters. Typical values of a and δ are 1.13 and 1.26 as given in Reference 6.

Because the Fraunhofer diffraction theory deals with light that passes near a particle, and not refracted or reflected light, the forward lobe scattering method enjoys the advantage of sizing mean diameter without having to know the particle's index of refraction or the concentration of the soot cloud. This method does assume, however, that the particle distribution is monomodal.

The incident light sources consisted of 632.8 nm laser light source in the aft exhaust scattering station, 632.8 nm laser light at the augmentor exhaust scattering station, and a 488.0 nm laser light source forward at the combustor can scattering station.

The photodiodes were located at various scattering angles (θ). At the combustor and exhaust scattering stations diodes were positioned at 20° and 40°. The augmentor tube exhaust scattering station consisted to three photodiodes positioned originally at -5°, 10°, and 20°. It is worth mentioning that larger particles diffract most of the incident light at smaller angles and smaller particles diffract more of the incident light at higher angles. Particles of near one micron in size were anticipated at the augmentor station, whereas particles near .25 microns were expected in the combustor can.

Equation (5) first appears overwhelming but in-fact was quite easily evaluated using incremented numerical integration. The Bessel function $J_1(\alpha\theta\xi)$ was used with increments of integration of $\Delta\xi = .1$ and values of D_{32} were considered from .05 microns to 1.0 microns. The Fraunhofer diffraction function $F(\theta)$ could then be solved for various scattering angles and incident light wavelengths.

The diffraction functions were ratioed for all five possible $F(\theta_1)/F(\theta_2)$ ratio combinations and were plotted vs. the mean soot diameter (D_{32}) in Figures 14, 15, 16, and 17.

The intensity ratios of the scattered light were calculated from the measured diode voltages. To reference all measurements to the same scattering volume, the intensities were multiplied by the sine of the scattering angle ($\sin\theta$). The plots of Fraunhofer diffraction ratio $F(\theta_1/F\theta_2)$ versus mean particle diameter D_{32} for the specific scattering station could be entered directly with known intensity ratios $\sin\theta_1 \times I(\theta_1)/\sin\theta_2 \times I(\theta_2)$ because

$$\frac{\sin\theta_1 \times I(\theta_1)}{\sin\theta_2 \times I(\theta_2)} = \frac{F(\theta_1)}{F(\theta_2)} \quad . \qquad (4)$$

The advantage of using both forward scattering and three wavelength transmittance measurements at a particular sizing station is that, with scattering, the

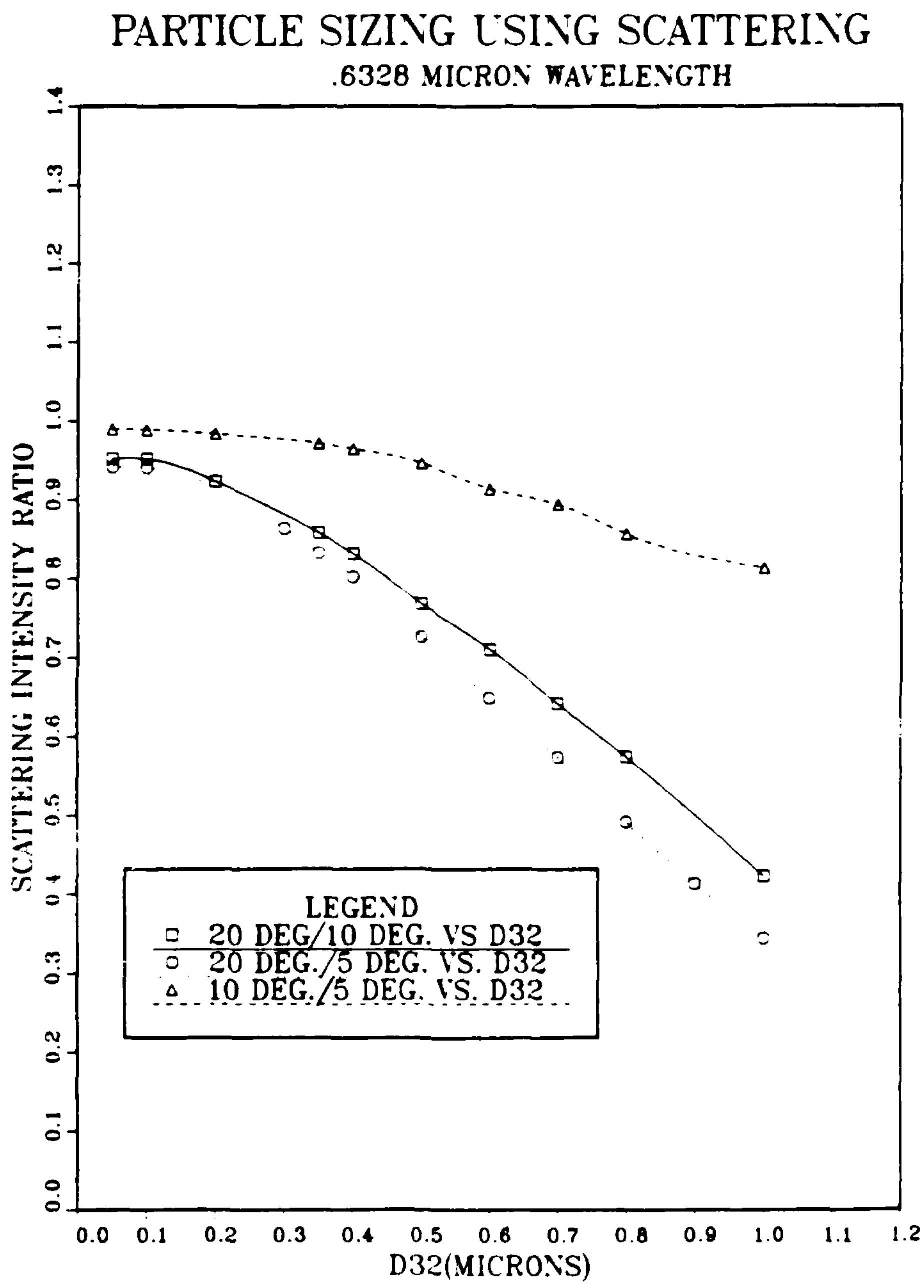


FIGURE 14. INTENSITY RATIO VERSUS D32

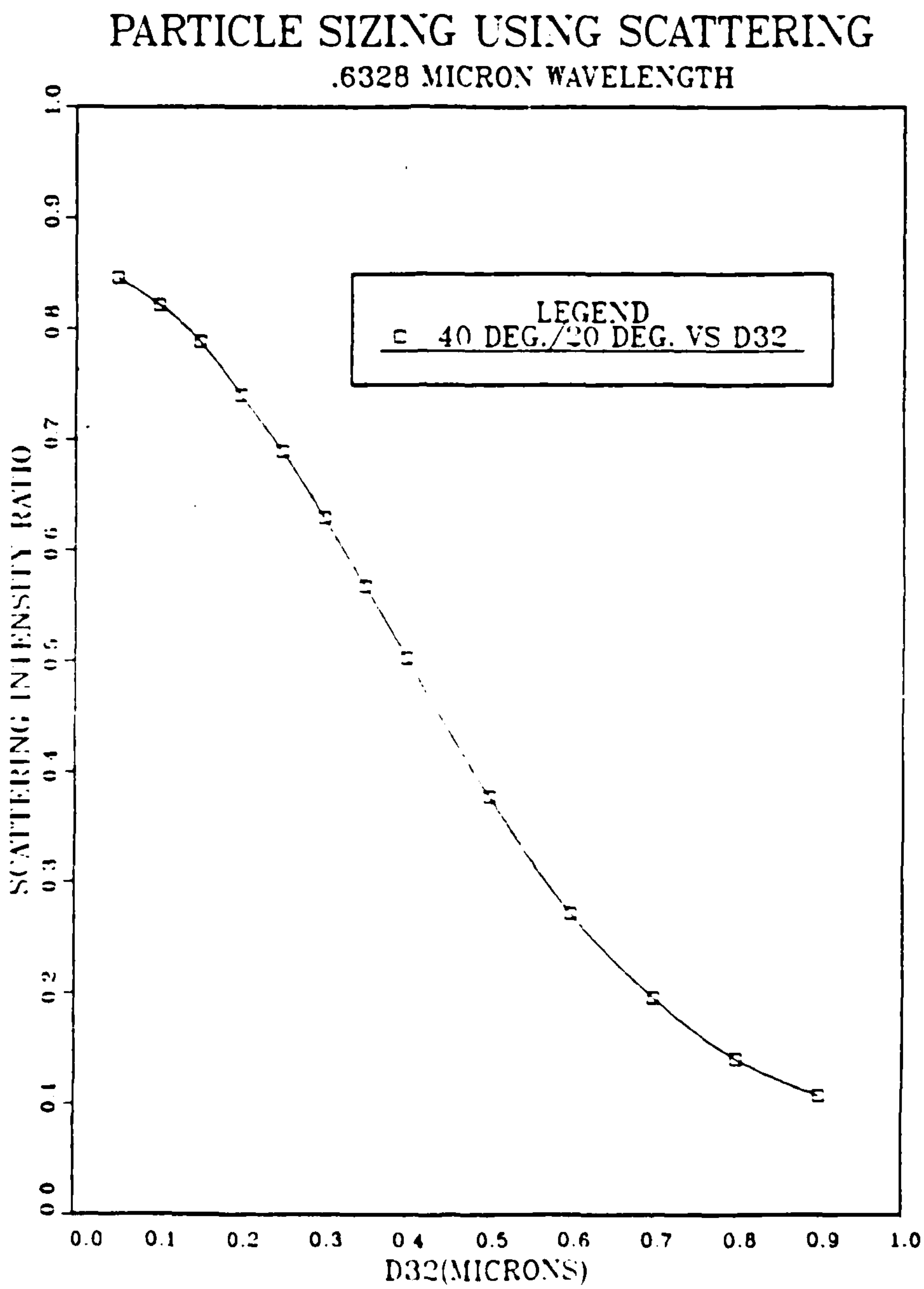


FIGURE 15. INTENSITY RATIO VERSUS D_{32}

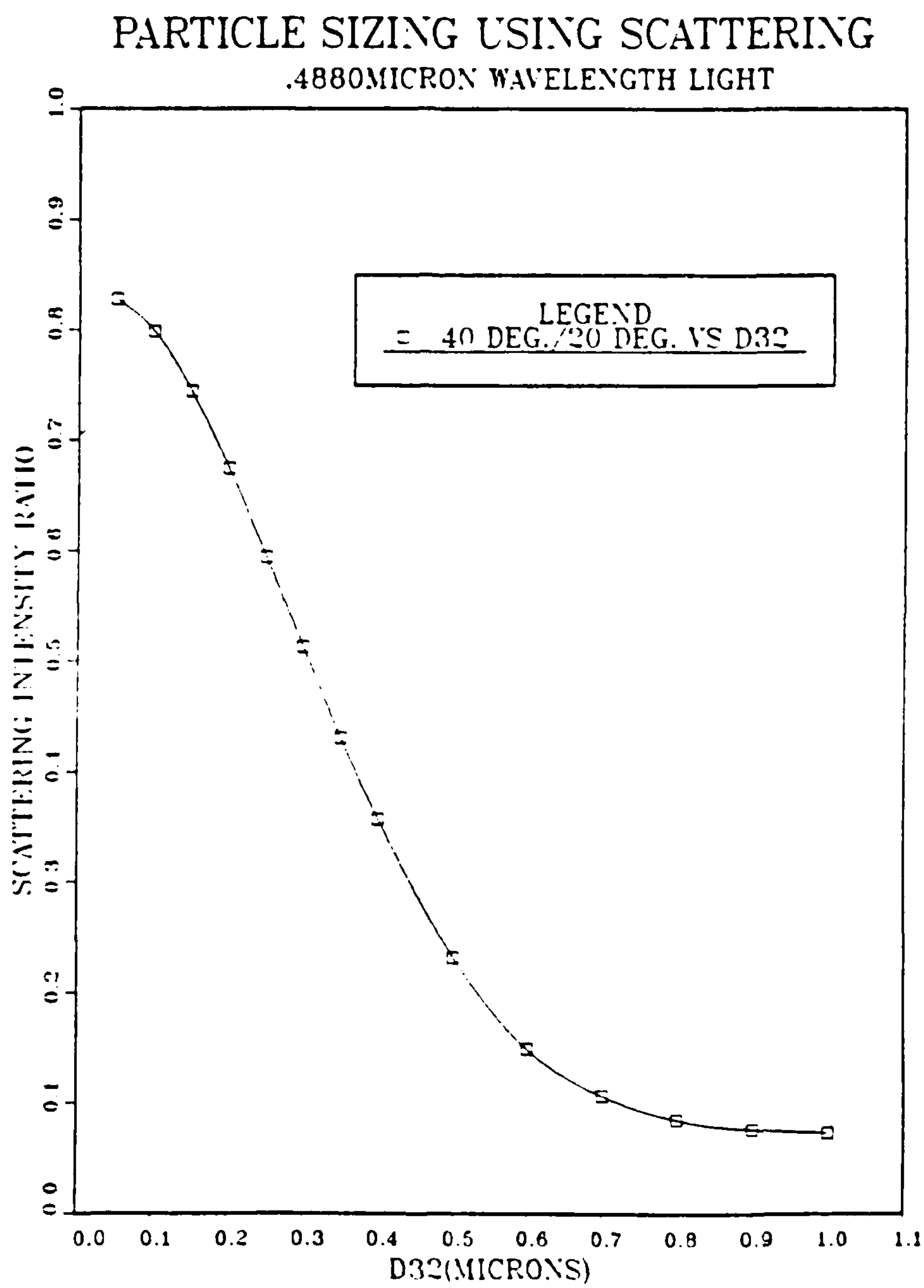


FIGURE 16. INTENSITY RATIO VERSUS D_{32}

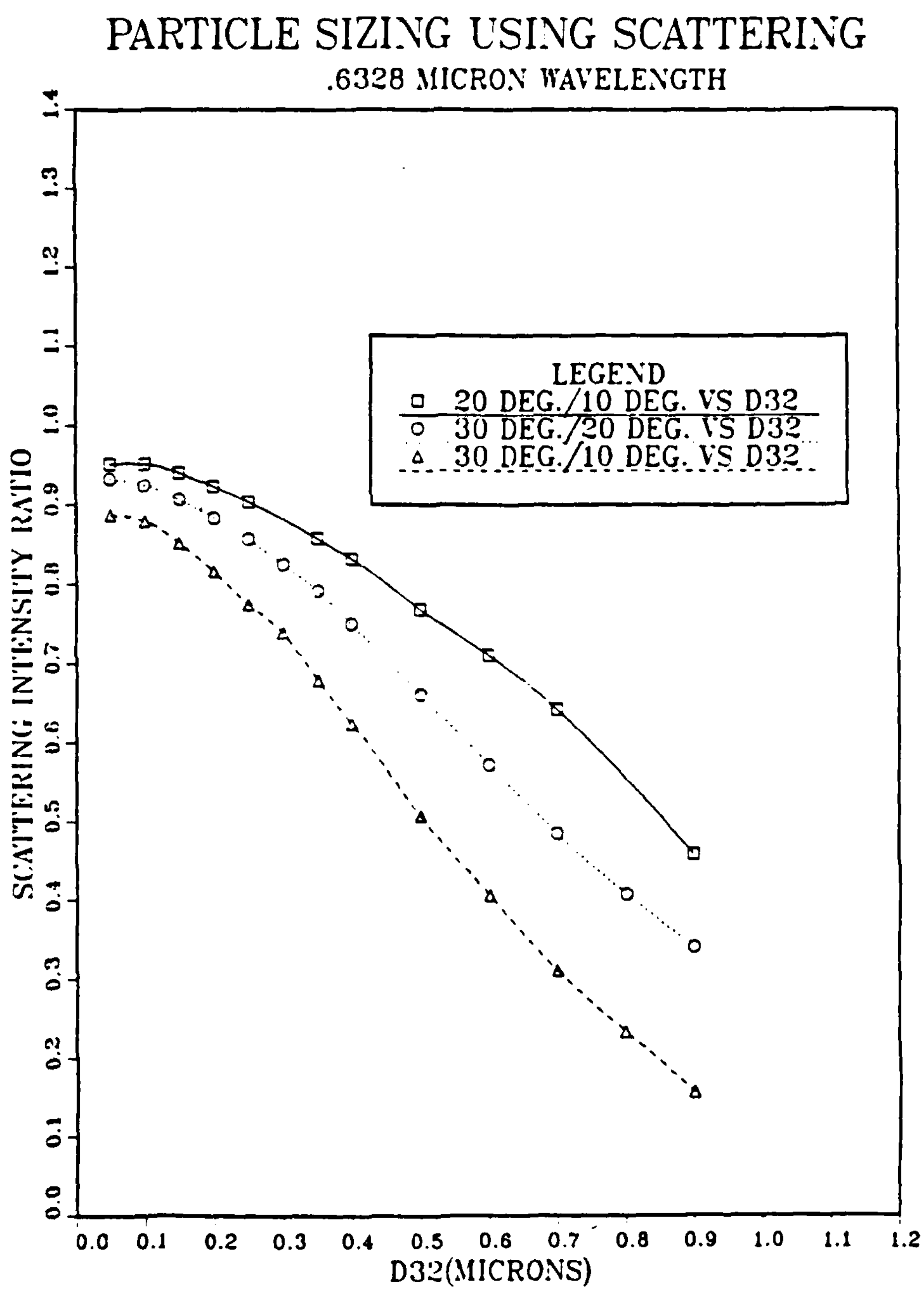


FIGURE 17. INTENSITY RATIO VERSUS D_{32}

particle's mean diameter (D_{32}) can be found without knowing anything about the particle's index of refraction. With D_{32} known, transmittance data yield the particle's index of refraction, and the particle concentration. Figure 18 graphically depicts the aforementioned procedure.

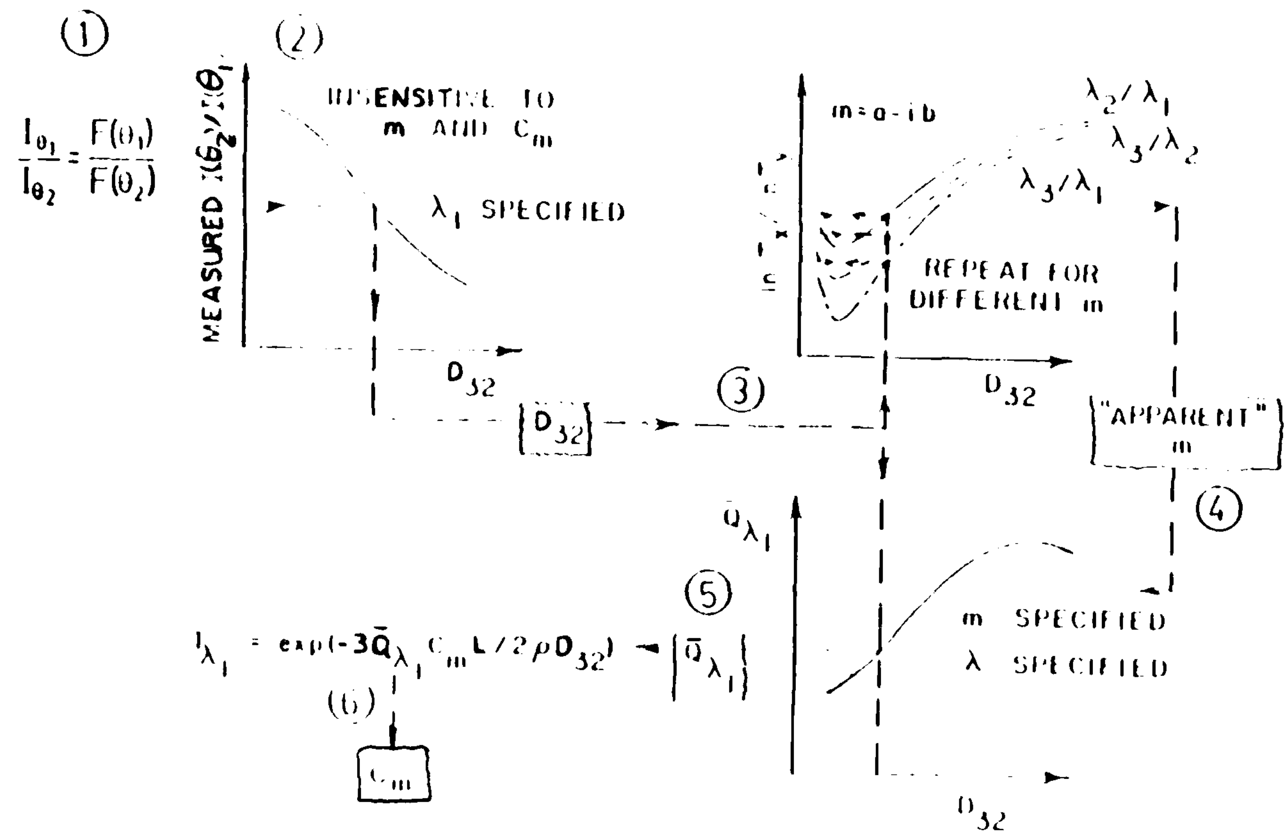


FIGURE 18. COMBINATION PARTICLE SIZING METHOD
(Adapted from Ref. 7)

IV. EXPERIMENTAL PROCEDURE

Prior to any data collection, several pre-test checks of equipment had to be made.

All transducers required calibration so that up-to-date calibration constants and zero values could be found and entered into the data reduction computer program. The transducers were used to measure main-air, quench-air, and engine chamber pressures as well as air heater fuel and oxygen pressure measurements. Recalibration of these transducers was performed periodically.

All five lasers were checked using an optical power meter to ensure that laser beam power was steady within a tolerance of about plus or minus 10 microvolts. This test had to be performed once; however, the results of this testing was kept in mind during data analysis.

All narrow-pass filters were checked to ensure that the filter met published specifications. This test was done by placing a laser with a known wavelength on an optics table and placing the narrow-pass filter in front of the laser and noting the attenuation of the beam aft of the filter.

The seven scattering diode boxes and six transmittance diodes required the most frequent checks prior to data collection runs. The first equipment check was a

geometric test to see if the narrow-pass filters and diode faces were perpendicular to the incident light sources. Shimming of filters was often required to make fine adjustments. Next, mirrors were used at the augmentor sizing station diodes to help sight the barrel centers of the diode boxes to the laser beam. This test was performed every time the diodes were removed and replaced from the apparatus.

Calibration of the seven scattering diodes was completed and their calibration constants were input into the data reduction computer program. Diode calibration was done by taking the diodes that were indigenous to a measuring station, positioning them on an optics bench in front of their particular laser used in the experiment, filtering the laser beam with neutral density filters to a low, but constant, voltage output and taking readings of the various diode voltages. All the diode sensitivities at a particular measuring station could be made to appear uniform by mathematically adjusting the weaker diodes with an adjustment value called a calibration constant. The pre-test procedure was performed periodically.

Another pre-test of light measuring equipment was a smoke test. Smoke was injected into the engine upstream to the scattering diodes. As the smoke passed the light scattering measurement station, the intensity voltages

were read. The voltages should increase nearly twice as much for a diode at 20° than say a 40° diode because the 20° diode had a larger field of view and, therefore, saw more diffracted light.

The trifurcated fiber optics cables were checked to ensure that they squarely faced the incident light source. It was found that the slightest angular deviation from perpendicular greatly distorted the optical detection capability of the cable.

The optical windows were checked at least every other run for lucidity. Often after a fuel rich run, residual fuel overpowered the nitrogen window purge gas and increased the opacity of the viewport window. This would greatly attenuate the intensity of the incident light beam.

After all of the aforementioned checks were completed, the actual hot run checklist would be referred to. The appendix contains a complete checklist.

After the run, data reduction was completed in four main subgroups. The pre-ignition data were taken with only main air on. Post-ignition data was also taken with only main air on. Both of these data reduction subgroups provide 100% transmittance readings to be compared with the hot run transmittance data. The hot run data, as the name implied, provided engine combustion data which were used for scattering and transmittance

calculations. The final data subgroup was additive data. This data could be used to calculate the increase or decrease in particle size and concentration caused by the additive material. During each run the following data were recorded/calculated by the data acquisition system:

- air flow rate
- fuel flow rate
- fuel-air ratio
- air pressure
- air temperature
- combustor exhaust temperature
- by-pass air pressure
- main combustor temperature
- signal voltages for transmitted light
- signal voltages for scattered light

V. DISCUSSION OF RESULTS

The experimental investigation was to have consisted of three stages. The first was apparatus modification and verification, the second was to explore how soot particle size is effected by various fuel additives in several different types of fuels, and the third was to examine the effect that augmentation ratio had on augmentor tube exhaust particle size. Because of a faulty air compressor, which limited the quantity of compressed air, and difficulties with some of the instrumentation, only fifteen data-gathering runs were made. The first stage of the planned experimental effort was successfully completed.

All of the test runs were made using NAPC-2 fuel. No additives were used. The fuel-to-air ratio for all runs was .0180.

Young [Ref. 1] concluded that the augmentor exhaust soot particle size was a mixture of medium to large particles (42% between 1.2 and 1.4 microns and 41% between .5 and 1.2 microns) and recommended that the augmentor tube photodiode geometry be changed. Based upon the expected particle size distribution, a diode configuration of 10°, 20°, and 30° or 5°, 10°, and 15° was desired. The first eleven runs were made with the augmentor tube photodiode geomtric configuration set at

−5°, 10°, and 20°. Because of the physical limitation caused by diode box size, the only positive small angle of diode placement was 3°. This set was unsuccessful because too much laser beam noise was detected by the diode. The laser light beam was modified (Figure 10) with a pinhole placed ten inches from the point of interest. The purpose of the pinhole was to clean the incident laser beam by eliminating much of the beam's noise. Although the pinhole eliminated much of the noise, the diode still sensed at least 50 millivolts of light energy from the laser at 3°. The photodiode box set at −5° also detected a 20 millivolt intrusion by incident laser beam light and, as a result, the only meaningful augmentor photodiode geometric configuration was at 10°, 20°, and 30°.

For various reasons, the first four runs yielded no useable data. In nine of the remaining eleven data runs, an exhaust mean particle diameter size of between .77 microns and .82 microns was measured using scattered light at the 20° and 10° augmentor photodiodes. The 30° diode, which was previously positioned at both 3° and −5°, produced scattering intensity ratios that supported this mean particle diameter range in only one of the eleven significant data runs. The other ten data sets which incorporated readings from the 30° diode were erratic because the 30° diode readings were consistently too high.

It is believed that the inconsistency in the scattering data was caused by the sensitivity of the measured light to small changes in alignment of the optical components. Each diode tube had to be aligned so that the laser beam passed across its diameter. Small displacements from this location could significantly reduce the scattering volume of particles that was detected. A possible solution to this would be (1) to increase the laser power, (2) to increase the beam diameter, (3) to reduce the diode tube internal diameter to the point where it is smaller than the laser beam, and (4) to incorporate more sensitive photodiodes.

No scattering data was obtained at either the combustor particle sizing station or at the engine exhaust sizing station. As previously recommended, a more powerful (15 nm) argon laser, tuned to a 488.0 nm wavelength,was used as the incident light source for forward scattering in the combustor. In the eighth data run it was discovered that the scattering diodes were being saturated with 488.0 nm light. This is a blue colored light. It was postulated that the combustion light was primarily blue in color. The incident light source had to be changed to another wavelength. A He-Ne laser (632.6 nm) was tried. Again, the scattering diodes were saturated.

The engine exhaust scattering station also did not yield any useable data. It used only a 632.8 nm incident laser light source. In the combustor section the laser beam passes through both the annulus of gas flow that exits the apparatus as well as a large central recirculation zone. The light that reached the position where scattered light was to be measured was severely attenuated. It will probably be necessary to change the forward optical path so that the beam passes only through the annular flow region if meaningful scattering data is to be obtained. This would reduce the beam attenuation and also minimize light from the combustor can wall from reaching the diode. Another problem with the current apparatus is applicable to all of the scattering measurements; the accuracy of the alignment/manufacturing process that determines the scattering volume seen by each diode. A calibrated rod, equal in diameter to the laser beam could be inserted through the combustor to provide a more accurate alignment.

The first ten data runs produced non-usable data from the combustor and exhaust transmittance sizing stations for two significant reasons. First, the trifurcated fiber optic cables were found through trial and error to give inconsistent data. It was discovered that even the slightest angular movement of the cable's receiving face would cause a very large diode intensity

voltage change. Additionally, the receiving face of the optical cable had varied sensitivities to light. The slightest movement of the incident light beam on the cable face would again cause significant diode intensity voltage changes. Prior to the eleventh data run, both cables were removed and replaced with the original diode box setup similar to that used by Young (Ref. 1).

The second cause of inconsistent data was the use of the phase-lock amplifier and chopper arrangement. It was found that the amount of transmitted light which passed through the combustor section was too small compared to the amount of combustion light. The phase-lock amplifier could not recognize and amplify the relatively small amounts of transmitted light deciphered from the combustion light signal. As a result, the phase-lock amplifier was by-passed and the chopper was removed. The data reduction program was modified with a simpler laser-on/laser-off data collection strategy. This method simply recorded the transmittance photodiode voltages with the lasers off and with the lasers on. The difference between the two voltages, adjusted for their initial zero-light values, was the amount of transmitted light voltage. The percent transmittance was then found simply by dividing the transmitted light voltage by the transmitted voltage tabulated with either pre-ignition air or post-ignition air. Using this

simple technique, strip charts could be used to check computer generated data.

In the four data collection runs available with the aforementioned modifications incorporated, neither the combustor transmittance sizing station nor the engine exhaust sizing station produced complete, consistent data. The combustor transmittance station on two runs, utilizing the logarithm ratios of 632.8 nm to 514.5 nm and 632.8 nm to 488.0 nm, produced a combustor mean particle diameter between .22 microns and .25 microns. These values correlated on the Mie-scattering plot with a refractive index of 1.95 -.66i with a standard deviation of 1.5. A three wavelength data correlation was not found in the combustor section in any of the data runs using either strip chart or computer data. The transmittance data was well behaved, i.e., transmittance increased with the wavelength of incident light and the diode voltages were very steady through the run. Three primary problems existed: (1) the transmitted light intensity was only a small fraction of the combustion generated light intensity, (2) the available lasers had wavelengths very close together, limiting accuracy of the extinction coefficient ratio plots, and (3) the optical path passed through two distinctly different combustion regions (discussed above). The 514.5/488.0 ratio was particularly small (1.05) and, therefore, could not be expected to yield consistent data.

The transmittance data from the exhaust sizing station was very inconsistent. For reasons not resolved in this thesis, the transmittance photodiodes sensed more transmitted light after engine ignition than they did with pre-ignition air or with post-ignition air. This phenomena could occur for various reasons, two of which are obvious. The first could have been engine/-optical window movement. The engine was thoroughly braced in vertical and lateral directions and the tests were repeated with the same results. Window movement was also examined and found not to be the source of the voltage increase.

The second possible cause could be that the photo-diodes were sensing infrared light from the hot gases or combustor walls. An infrared filter was placed in front of all three sensing diodes during a test firing, and once again, the photodiode transmittance voltages during the run were greater than with the air only portions of the test.

Another possibility for the behavior was the existence of liquid fuel or fuel vapor in the window support tubes before the run was initiated. If this is resolved to be the problem, window shutters could be installed which remain in place until after ignition is attained.

VI. CONCLUSIONS AND RECOMMENDATIONS

The air quench modification was successfully installed and operated and reduced the exhaust gas temperature by approximately 190° Fahrenheit. With the inconsistent data obtained at the combustor sizing station and the engine exhaust sizing station, it was not possible to obtain accurate particle sizing using a combined transmittance and scattering sizing technique within the T-63 combustor.

The most consistent data was obtained at the augmentor exhaust where the particle size exiting the augmentor tube was measured to be between .77 microns and .80 microns. The 10° and 20° data correlation was high However, the 30° diode read consistently high during the entire experiment, and only once supported the 10° and 20° data. Several modifications should be made. The existing photodiodes should be replaced with more sensitive ones so that the scattered light intensity would have them operating near their mid-range value. An alternate equipment improvement might be to replace the existing laser with a more powerful one which has a wider, more intense beam. The diode box view ports could then be blocked with a centered pinhole. This would provide a more easily aligned augmentor scattering measurement apparatus. A final recommendation to the

augmentor sizing station would be to utilize a single diode box which slowly rotated through a specified arc length to measure scattering intensities at various angles. This would eliminate the need for calibration constants,which attempt to compensate for various photodiode sensitivities, and may reduce the significant errors introduced from even the slightest angular misalignment of the current individual diode boxes.

With the existing design, it remains doubtful that scattering data within the T-63 will ever be consistently accurate. Combustion light, radiation from hot engine parts, and exact scattering tube alignment are possible causes for the inconsistent results. The measurement tubes should be carefully realigned, and it may be necessary to move the combustion zone measurements into the annular flow region. More sensitive diodes should also be employed.

The trifurcated fiber optics cables proved too sensitive to angular movements for use with transmittance measurements at the combustor and exhaust stations. Additionally, because of diverse sensitivities on the cable's receiving face, it is recommended that they not be used in the future with this apparatus.

Finally, the mystery as to why all three diode voltage readings, at the aft transmittance sizing station, sensed more transmittance voltage during the hot

run than during both pre-ignition and post-ignition must be readdressed. Engine movement, infrared light, and faulty window purge were all tested and discounted as possible causes for this phenomena. Additionally, this occurrence was found not to be related to a change in pressure.

APPENDIX

RUN CHECKLIST

Nitrogen Bottle Room

1. Turn on control nitrogen. Ensure at least 1000 psi.
2. Turn on actuator nitrogen. Ensure at least 500 psi in bottle.

Fuel Storage Room

1. Open nitrogen bottle valve (1000 psi minimum).
2. Adjust hand loader to read 750 psi.
3. Slowly open valve leading up to 20 gallon fuel tank.
4. Very slowly open valve leading from near bottom of the tank to the T-63.

Outside

1. Ensure main air valve is full open.

AT THE RIG

1. Turn on large argon laser using it's printed checklist.
2. Connect nitrogen window purge line (650 psi minimum pressure at bottle).
3. Turn on power supplies:
   a. Power supply for diode amplifier and signal conditioner.
   b. Power to phase-lock amplified.
   c. Power to both transmittance boxes.
   d. Power supply to augmentor diode amplifier and signal conditioner.
4. Turn on power supply to chopper.
5. Position both yellow and blue main air shut-off valves to ON.
6. Connect flex hose for quench air.
7. Check ignitor plug for security.
8. Ensure thermocouple power supplies are ON.
9. Check laser alignment and read all transmittance voltages.
10. Check white-light source collimation and alignment. Read all transmittance voltages.
11. Ensure laser shutter ON and in T position.
12. Go inside and turn ON computer. Run "T-63" in order to turn on both aft helium-neon lasers.
13. Check alignment of aft lasers.

14. Cover transmittance sight ports with black tape and go to computer to record transmittance zeros for data reduction.
15. Also mark strip chart zero positions, as necessary.
16. Remove tape covers.

INSIDE CONTROL ROOM

1. Turn ON both master-on switches at control panel.
2. Set fuel pressure guage at 475 psi.
3. Set main at air 650 psi.
4. Ensure three main ON-OFF switches are ON for electronic equipment racks.
5. Ensure printer is on-line.

HOT RUN START

1. Check for golfers.
2. Air only on, window purge on, check pre-air setting.
3. Turn on siren.
4. Start strip charts.
5. Air on.
6. Ignitors cycle.
7. Fuel on, check fuel flow .34 GPM. Check for wet start.
8. After data gathered, fuel-off.
9. Main air on until engine cool down is complete.
10. Main air OFF.
11. Record run time.
12. Complete shut down procedures.

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